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Nanolasers based on nanowires and surface plasmons

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New 1D laser designs and improved physical insights can potentially lead to development of the smallest lasers.

Development of nanolasers has been an active area of research for quite a number of years. The overall goal is to make lasers as small as possible or—more quantitatively, as a Defense Advanced Research Projects Agency program[1] challenges—to produce a laser that is smaller than a single wavelength in all three spatial dimensions. Although this would be an important length limit to overcome, we have realized that the more immediate obstacle is to have sufficient gain-material length or enough optical (or modal) gain to overcome a variety of light losses. Approaches using nanowires and surface plasmons offer potentially large modal gains and thus appear to be promising.

Semiconductor nanowires are 1D structures with high length-diameter aspect ratios, with typical diameters of tens to hundreds of nanometers and lengths of tens to hundreds of microns. A single nanowire can act as a nanolaser[2–4] because it simultaneously provides both a gain medium and a waveguide. As optical waveguides, nanowires have two unique features: their diameter is comparable to the wavelength and the refractive-index contrast (between semiconductor and air) is large. Our research shows that this results in many unique nanowire-laser properties, including a confinement factor (the ratio of modal to material gain) greater than unity,[5] strongly frequency- and diameter-dependent facet reflectivities,[6] and a very nontrivial far-field emission pattern (see Figure 1).[7]

A confinement factor greater than unity used to be controversial. However, the conventional definition—the field-energy ratio inside the gain medium to the total—is only valid if the field is essentially a paraxial scalar field. More generally (such as in nanowires), we have shown that the confinement factor needs to be generalized mathematically to keep the original physical meaning.[5] The larger confinement factor represents an important advantage, allowing nanowires to operate as lasers. The smallest nanowire lasers have dimensions of approximately 100–200nm in diameter and a few microns in length. Even though they can be made very small, the challenge is to make nanowires lase under electrical injection. A proper understanding of nanoscale p-n junctions[8] and metal contacts,[9] as well as a

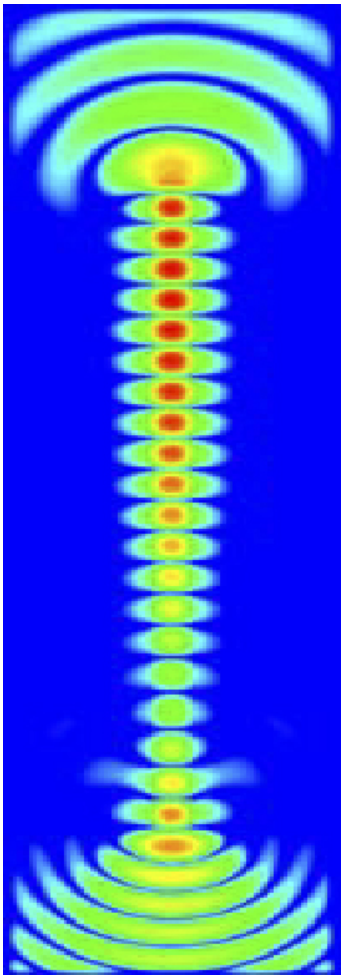

Figure 1. *Intensity profile along a nanowire vertically positioned on a substrate. Light, characterized by a nonplanar-field front, is emitted more strongly into the substrate than into the top end.*

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proper junction configuration[8]—all of which have been studied systematically by our group—are essential. Controlled doping and fabrication of metal contacts are critical and currently under intense systematic investigation worldwide.

As the nanowire diameter is reduced to smaller than approximately half the medium's wavelength, wave guiding becomes poor. This significant reduction in confinement factor is the main reason that small nanowires do not lase. We recently proposed that a metal coating could be used to improve the modal confinement.[10] This semiconductor-core metal-shell structure was one of the first integrated metal-semiconductor structures to be studied systematically[10] to determine if there might be a modal gain in such a seemingly lossy structure. Although a metal-dielectric structure near the plasma resonance allows a dramatic reduction in the effective wavelength,[11] it was not clear how large the loss would be. It is thus important to determine both the confinement and loss (or gain) in any metal-semiconductor structure intended for laser applications.

Our recent results show that the metal loss is prohibitively large and cannot be overcome by the highest material gain even in the best semiconductor *near plasmon resonance*, where the wavelength compression is maximal or where plasmonic effects allow the strongest reduction in device size. Somewhat unexpectedly, however, we found that a frequency band exists (below plasmon resonance) where the overall modal gain is positive for a large enough material gain in the semiconductor core. We also noted that the confinement factor can be exceedingly large near the cutoff wavelength. Although the required gain is still large (several thousand per centimeter), design improvements and operation at lower temperatures would definitely make such a design workable. Indeed, it was shown that a metal-coated semiconductor pillar structure can operate as a laser. A gold-coated semiconductor pillar etched from a standard indium-phosphide-based laser structure works as the smallest semiconductor laser.[12] We are currently developing design improvements, and some exciting new results have already been achieved.

Miniaturization in photonics is a never-ending process. It leads to newer and smaller devices, including nanolasers. The small devices will challenge fabrication technology and device design, as well as our physical understanding of device physics and the interaction between light and metal-semiconductor integrated structures. New designs and improved understanding may lead to devices that are not only small but also qualitatively new.

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